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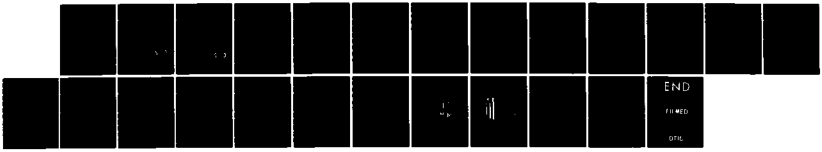

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R.L. Woodward & B.J. Baxter

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This report reviews Australian contributions to research in high rate deformation studies with particular reference to penetration mechanics and armour. Computationally efficient models have been developed which facilitate rapid and inexpensive predictions of penetration behaviour. The scope and accuracy of various computational methods are discussed, together with some practical applications. A bibliography lists the major publications in subject areas of relevance.

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POSTAL ADDRESS: Director, Materials Research Laboratories
P.O. Box 50, Ascot Vale, Victoria 3032, Australia

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AUTHOR(S)	CORPORATE AUTHOR
R.L. Woodward & B.J. Baxter	Materials Research Laboratories P.O. Box 50, Ascot Vale, Victoria 3032

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C O N T E N T S

		Page No.
1.	INTRODUCTION	1
2.	RESEARCH ASPECTS	1
3.	PRACTICAL DEVELOPMENTS	5
4.	ACKNOWLEDGEMENTS	5
5.	REFERENCES	6
6.	BIBLIOGRAPHY	9

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PENETRATOR/ARMOUR INTERACTIONS - BACKGROUND

TO AUSTRALIAN WORK

1. INTRODUCTION

Research into penetration mechanics and armour is conducted in Australia at the Materials Research Laboratories, Maribyrnong. To highlight the approaches adopted and the techniques used to meet our requirements, the most appropriate course is to review the work, examine its proposed directions, and to discuss some developments and practical applications.

2. RESEARCH ASPECTS

(a) Deformation Mechanisms

Penetration mechanics research at MRL, has concentrated on mechanisms and geometry of plastic flow, adiabatic shear and fracture phenomena, and the influences that material structure and mechanical properties have on performance. Early work centred in particular on understanding adiabatic shear, and highlighted the effect that this phenomenon can have on limiting the performance of armours and penetrators [1]. The mechanism proposed of Zener and Hollomon [2], that adiabatic shear is an instability associated with the rate of thermal softening exceeding the rate of work hardening allows materials to be classified in terms of their relative susceptability to adiabatic shear using simple calculations. The order of this classification agrees qualitatively with experiments [3,4]. Extensive microstructural investigations have confirmed narrow bands of intense shear and simple calculations show that high local temperatures are to be expected in association with the large strains [5]. The influence of adiabatic shear on the performance of targets has been shown to depend on obliquity of impact [6] and in some cases also depends on material structure [7,8]. A simple

model has been developed to describe the mechanism of adiabatic shear plugging failures and to allow approximate calculations of ballistic resistance from material strength [9]. Recent work in the US demonstrated that with the use of a thermal softening criterion it is possible to simulate the separation of a plug from a target using the EPIC-2 computer code [10].

There are still many uncertainties about the nucleation of adiabatic shear bands [7]. Basic studies of the theory have shown reasonable agreement with experiment in some cases [11,12,13), and in others have led to the suggestion of alternative mechanisms [14,15,16]. Temperature rises at shear band nucleation have been measured and calculated in the range 50°C to 200°C [17,18], which raises questions concerning the earlier mentioned microstructural, post-event, estimates of much higher temperatures. However, this apparent discrepancy can be explained as nucleation and only requires that the rate of thermal softening exceed the rate of work hardening as a precursor to the development of high strains. Some target failures attributed to adiabatic shear have been shown to by only nucleated by adiabatic shear, while target perforation occurred primarily be a conventional fracture mechanism [7,8]. Adiabatic shear is also a recognized deformation and fracture mechanism in penetrators. Work is continuing at MRL to examine aspects of composition and heat treatment on work hardening rates in steels, comparisons of the ballistic performance of steels produced by different manufacturing techniques, and examination of some aspects of adiabatic shear in very thin targets. As the phenomenon becomes better understood it is hoped to learn better ways to avoid it where it is detrimental to performance, and perhaps penetration and target performance can be improved by minimizing its occurence.

Many targets fail in a ductile manner. Microstructural examinations at MRL have led to descriptive deformation models, to be discussed below, which are useful in relating the mechanical properties to the ballistic limit. More important than this, it is possible to relate microstructural features and geometric aspects of the impact conditions (projectile shape, target thickness, obliquity) to the likely mode of failure [8]. The methods used in the manufacture of metals lead to significant directionality in mechanical properties. Anisotropy in both plastic deformation and fracture properties results from texture effects (preferred crystal orientation), residual stresses, chemical segregation and the distribution of non-metallic inclusions. These factors significantly affect ballistic behaviour.

Modelling and computational approaches can never be completely satisfactory as the cost of characterizing the material, combined with the difficulties of adequately describing the effects succinctly in a mathematical form will remain prohibitive except in a few special cases. The issue is illustrated by the photograph shown in Fig. 1 of three tensile specimens which were taken in three mutually perpendicular directions from a UK manufactured 70 mm thick rolled homogeneous armour plate. The properties measured in the three directions are tabulated in Table I and illustrate the effects of anisotropy, particularly ductility. Conventionally the results of mechanical tests in one direction only are used in computations but a ballistic test is influenced by properties in all directions. The most appropriate method is to

observe mechanisms, model the main features, and develop an appreciation of the likely effects of material structure on ballistic performance. Since fracture particularly influences behind armour effects, these observations do not encourage the pursuit of quantitative micromechanical descriptions of ballistic experiments as the principal aim of penetration mechanics research.

(b) Mechanics

Studies of deformation mechanisms have led to a number of classifications of target failure [8,19] and also to the development of models which allow penetration resistance to be related to mechanical properties. The problem remains simple if the projectile does not deform, and work at MRL has tested, improved and developed a number of models for ductile hole formation [20], dishing [20], discing [8,21], ductile plugging [22], and adiabatic shear plugging [9] failures which have been particularly useful. There is a large range of models which treat different aspects of the penetration problem. The models range from those which simplify the problem sufficiently to make the method predictive, to those which require post perforation target measurements and are therefore descriptive [19]. When used carefully the models give valuable quantitative information and they embrace an understanding of the mechanics as conceived by the model developer. The models, by taking a variety of approaches, are complementary and contribute to the development of correct concepts.

A more complex but more interesting problem in modelling the behavior of modern kinetic energy penetrators is the case where both penetrator and target deform. A model has been developed for the normal impact of a flat-ended cylindrical projectile on a semi-infinite target, and a number of tests have shown that the model gives good predictions of penetration behaviour which scale correctly with geometry and velocity [23,24,25]. The model becomes inaccurate at very high velocities as the limit to penetration depth with increasing velocity is approached, partly because the rod erosion mechanism which it uses is not realistic [25]. The model has been used for a number of studies of the effects of length to diameter ratio and material properties on penetrator performance. Whilst the restriction to cylindrical geometry limits its use, the model has been of great assistance in investigating the deformation of the nose of the penetrator, particularly the enhanced penetration effects first reported by Brookes and Erikson [26,27,28]. Because ballistic data is available under similar conditions for both semi-infinite and finite thickness targets [29], it is possible to estimate the results of firings against finite thickness targets using such a model.

An aspect of considerable interest in the deformation of slender penetrators is rod bending. Currently we are adapting a simplified approach to studying the bending of notched and unnotched rods, by using a static rod supported at one end and subjected to transverse impact at the unsupported end by a short cylinder. The deformation is monitored with strain gauges and flash radiography as well as post event measurements of strain distributions. Use has been made of the EPIC-2 code to simulate the event and

to demonstrate some of the wave propagation aspects, and additionally it appears that simple rigid/plastic deformation models are a useful tool to study this event. Figure 2 shows the effect of notching a rod on the distribution of bending strain using flash radiographs. Such a simple approach allows simple experimentation for the development of understanding, but only provides part of the answers for real system development.

It is essential to have an understanding of the accuracy and essential value of both model and computational techniques. Models, which treat a simplified problem using a combination of analytical solutions and numercial techniques, and codes, which attempt a full numerical simulation of the problem, are complementary and lead to a useful understanding of deformation mechanisms and the effects of changes in materials and configurations. The models are limited in scope by simplifying the problem. However, they are computationally efficient and cost effective. Agreement between computed results and experiment is good if it is within the order of twenty percent, as this is really the limit of plasticity theory when combined with real material anisotropy, and the measurement and characterization of flow stress and fracture properties. For munitions development, the computational techniques provide initial bounding of possibilities, and allow mechanisms and design variations to be studied; however optimizing the detailed configuration of the munition will always require expensive trials. The objective of the computations is to reduce this cost, and there is a need to continually examine the cost of the computational approaches and the realiability of the answers in each case. A good understanding of deformation mechanisms also allows unusual concepts to be efficiently evaluated using the computational technique.

(c) Material Properties

Coincident with mechanics studies, it is essential to have valid data on material properties at high strain rates. MRL has a continuing effort on the use of high strain rate compression testing to characterize materials at high rates of strain [30]. In addition to providing basic strength data, information on adiabatic shear [31,32] and fracture can be obtained. Currently the behaviour of a range of tungsten alloys is being examined to see if dynamic properties can be related to penetrator performance.

It is important to distinguish spalling which is produced by stress wave reflections, and interactions from discing which is a failure mode influenced more by the bending deformation of the rear of a target [33]. Microstructure, anisotropy and toughness have an important influence on both of these mechanisms which essentially determine the behind armour debris from the target material. Spallation tests are being undertaken at MRL using a simple test, which has been modelled using EPIC-2 computer simulations to examine the relationship between the spall strength of a variety of armour materials and their structure, mechanical properties and processing history.

3. PRACTICAL DEVELOPMENTS

The value of the research tasks is partly realized through the benefits of exchange. Australian research, by making a contribution to the TTCP effort, receives information in return which would be too difficult for us to generate in both manpower and cost. To obtain a useful exchange, it is important to make a significant contribution by ensuring that the work is "state of the art" and complementary to that of other countries. The research runs concurrently with work on some practical problems. A high ductility tungsten alloy was developed for use in the Phalanx close-in weapons system. Investigations of armour have encompassed some unusual configurations and some valuable ballistic data has been generated.

Because of cost, vulnerability studies and penetrator assessments must be done by calculation. The calculation techniques use a combination of the models discussed earlier [34], with published experimental data where available, experience, and an invaluable guide to the performance of armour materials, that is, the tabulations produced by the Army Materials and Mechanics Research Centre [35]. Behind armour effects can only be estimated from a knowledge of the materials and their performances, however knowledge in this area has been advanced significantly by the work of the TTCP Action Group on Behind Armour Effects [36]. There is no substitute for tests where these are possible and assessments of materials and configurations for lightweight armour using ballistic tests are carried out at MRL. Complex configurations cannot be assessed properly using computational techniques.

In reviewing the contribution made by MRL to penetration mechanics research, the emphasis has been placed on describing the approaches adopted and the major concepts and directions. Detailed information can be obtained by reference to the bibliography.

4. ACKNOWLEDGEMENTS

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T A B L E 1

TENSILE PROPERTIES OF ROLLED HOMOGENEOUS ARMOUR PLATE IN THREE ORIENTATIONS

Orientation		.2% Proof (MPa)	U.T.S. (MPa)	Fracture Stress (MPa)	Redn Area %	Elongation %
Principal Directions in Plane of Plate	(A	676	822	1456	61	21
	(B	688	839	1478	62	22
Short Transverse		654	766	802	11	6

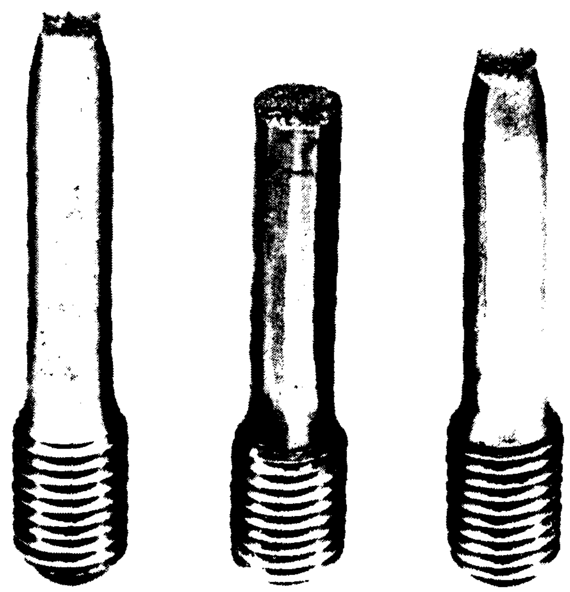

FIGURE 1. Tensile test pieces from rolled homogeneous armour, left and right are from principal directions, B and A respectively (Table 1), in the plane of the plate and the centre specimen is from the short transverse direction.

FIGURE 2. Comparison of the bending deformation of continuous and pre-cracked slender beams subjected to a transverse end impact at velocity of 775 m/s

(a) Continuous Beam, flash radiograph at 15, 30 and 50 microseconds after impact.

(b) Beam containing a crack, flash radiograph at 15, 20 and 25 microseconds after impact.

These radiographs also show the wires to be strain gauges together with the flash X-ray trigger wire.

(MRL-R-936)

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